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## Ames Life Science Telescience Testbed Evaluation

*Richard F. Haines, Vicki Johnson,  
Kristofer H. Vogelsong, and Walt Froloff*

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Research Institute for Advanced Computer Science  
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RIACS Technical Report 89.31



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## Ames Life Science Telescience Testbed Evaluation

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### ABSTRACT

*Eight surrogate spaceflight mission specialists participated in a real-time evaluation of remote coaching using the Ames Life Science Telescience Testbed facility. This facility consisted of three remotely located "nodes": (1) a prototype Space Station glovebox, (2) a ground control station, and (3) a principal investigator's (PI's) work area. The major objective of this project was to evaluate the effectiveness of telescience techniques and hardware to support three realistic remote coaching science procedures: plant seed germinator charging, plant sample acquisition and preservation, and remote plant observation with ground coaching. Each scenario was performed by a subject acting as flight mission specialist, interacting with a payload operations manager and a principal investigator expert. All three groups were physically isolated from each other yet linked by duplex audio and color video communication channels and networked computer workstations. Workload ratings were made by the flight and ground crewpersons immediately after completing their assigned tasks. Time to complete each scientific procedural step was recorded automatically. Two expert observers also made performance ratings and various error assessments. The results indicated that: (1) The overall quality of science performed increased when audio, video, and computer workstations were available, (2) Loss of video resulted in many errors that were not caught by the PI or ground controller. Most would have resulted in loss of the tissue sample. Others would have resulted in safety hazards and/or injury, (3) Once the subject was trained in a procedure they tended to use the computer-derived procedure checklist more as a backup only, (4) The audio channel was considered to be the single most crucial communication means of the three tested, (5) Physical workload is significantly reduced during runs when two-way color video is available than when it is not. Mental workload is not so influenced, (6) The rapid prototyping approach to hardware, software, and procedure validation is sound and cost effective.*

1. The first part of the document is a list of names and addresses of the members of the committee.

## INTRODUCTION

Telescience is an operational mode which enables the effective conduct of science through the use of remote resources including other people. Telescience may be subdivided into at least three principal components: teledesign, teleanalysis, and teleoperations. The Ames Life Science Telescience Testbed was designed as a rapid prototyping facility to evaluate teleoperations. Teleoperations is defined as:

Operation of a laboratory remotely by providing capabilities to allow full user interaction as if the instrumentation were physically present. In addition, teleoperations enables the conduct of intra-and inter-active science where immediate scientific results can be evaluated by the investigator in real time or new experiments can be carried out as new phenomena are uncovered.

Effectively planned and executed teleoperations should allow a scientist at his or her home institution to carry out an experiment remotely using realtime displays of all relevant scientific and telemetry data. Reliable interactive control of the instruments also should be possible. Of course certain limits may be imposed by safety, security, and resource constraints.

Telescience is valuable in carrying out life science experiments in space for a number of reasons. For one, the nature of this research differs from that in the physical sciences because the flight crew may serve both as experimenter and test subject. This fact calls for carefully planned test apparatus that can be monitored from the ground to ensure that the crew are well and the data is of adequate quality. For another, unexpected phenomena may occur which were not anticipated; the investigator may need to make real-time decisions to alter test conditions as the data is being collected. The application of properly designed telescience means of connectivity makes this possible. Life science experiments may also call for greater flexibility of planning and conducting the investigations than do physical science experiments. In addition, many life science procedures are time consuming and repetitive; remote semi-autonomous robotic mechanisms under telecontrol may be used to free up crew-time. The large computational power of computers, linking earth with the space station's telescience communication channels, also makes it possible to carry out intense, elegant, creative, and responsive ground analysis of realtime data.

### *Test Objectives:*

In order to ensure that the variety of claimed capabilities of teleoperations actually are achievable it is essential to carry out manned tests with representative, working hardware

and software. This evaluation had four primary objectives: (1) Demonstrate savings in crew time, flexibility of scheduling, enhanced productivity, and quality of science, if possible, within a semi-realistic test environment representing Space Station, (2) Evaluate interactional telescience modes using various combinations of flight crew, ground controller, ground expert, and a low fidelity autonomous system, (3) Measure crew performance and system impacts and means of coping with off-nominal events, and (4) Provide the capability for audio-visual teleconferencing, information transfer, and transaction management.

In this evaluation a number of interactions between representative operational elements and all participants were evaluated. The operational elements included three remotely located networked workstations and their collaborative software, duplex audio communication system, two-way closed circuit color TV networks, and a telerobotically controlled robot located inside the glovebox. The participants included a number of surrogate mission specialists, ground controller and ground scientist/expert. Details of the system's architecture are given elsewhere (Johnson, in preparation).

## METHOD

### *Experimental Design:*

The multifaceted objectives of this investigation called for a variety of participant groups and dependent measures. There were three participant groups and four quantitative measures of interest. The first group of participants was the eight test subjects who provided the following behavioral response measures: subjective workload estimates following each scenario, time to carry out each step in each scenario, and general comments and observations about the design of the glovebox, procedures, and any other subject of interest (immediately following completion of the test). The second participant group consisted of the ground controller (author RFH) located at the Payload Operations Control Center (POCC) and the principal investigator (author KV) located at the PI's station. Each provided subjective workload estimates following each scenario at the same time these estimates were given by the test subject, and general observations concerning the functioning of the hardware and the adequacy of the procedures. These comments generally were given after the conclusion of the study while some were offered during the study. The third participant group was the two expert raters (authors VJ, WF) who kept notes throughout the data collection period on the items listed in Appendix A.

Each subject carried out three life science glovebox science procedures (also called scenarios) a number of times during this investigation. One of the test approaches used was to ensure that each subject had reached performance asymptote during all three scenarios and then note changes in performance caused by the occurrence of an unanticipated failure. Performance during asymptotic response periods would also provide valuable insight about how the available telescience modes are used. Four types of failures were presented to evaluate the usefulness of the available telescience modes as described below. A second feature of the experimental design was to train half of the participants to operate with and the other



half without any computer networked support and then compare their performance. A third testing approach was to have half of the participants carry out the three scenarios without any video link so that their performance could be compared with the other half that did have two-way video.

To demonstrate anticipated advantages of these telescience technologies on crew time savings, scheduling flexibility, enhanced productivity, and science quality, a team of expert observers were asked to make periodic human and system performance judgments using the form shown in Appendix A. Analysis of video recordings, performance error analysis, and workload ratings were used to evaluate the effectiveness of the various telescience technologies employed (viz., computer-based prompting, two-way voice and video communications, pre-programmed telerobotic operations, and networked workstations with electronic mail). Insertion of an unanticipated system failure for each subject made it possible to evaluate the use of telescience technologies for coping with off-nominal events. The three specific science scenarios used were chosen to evaluate the utility of the teleconferencing and workstation collaboration capability as well as the effectiveness of information transfer.

*Workload Rating.* Using a standardized response menu which was available at their workstation, each subject, ground controller, and PI completed a workload rating series immediately following each scenario. As shown in Figure 1, which is a reproduction of the macintosh screen image presented, three workload measures were quantified: physical, mental, and total. The physical effort scale represented the subjectively determined amount of physical effort that had to be expended to accomplish all of the required tasks in a scenario. Likewise, the mental effort scale referred to the amount of mental effort, cognitive effort or concentration that had to be expended to accomplish all of the required tasks in a scenario. The total effort rating incorporated all of the contributors which make up one's own workload estimate (e.g., emotional response, intellectual involvement, psychological response, mental and physical workload). Total workload is not merely the sum of the physical and mental workload estimates.

Referring to Figure 1, when the subject clicked and held the mouse input to hold the cursor on the physical effort box a menu with seven numbered responses appeared: none, very low, low, medium, medium high, high, very high. When the mouse was dragged down this scale, stopped on the desired rating, and then released, that answer was input to a file for subsequent printout and analysis. These responses were available for inspection immediately after each group of trials, which proved to be a useful capability.

*Expert Ratings.* Each of the two ground experts used a special form to comment on and rate a variety of topics (cf. Appendix A). This was done during each scenario. This form contained the following issues and concerns: (1) Evidence for savings in crew time, scheduling flexibility improvements, productivity enhancement, science quality enhancement, and safety enhancement. (2) Demonstration(s) of workstation teleconferencing capability, video teleconferencing, audio teleconferencing, and effective information transfer. (3) General comments on space to ground, ground to space, ground to ground telescience interactions, and robotic operations. (4) Number and type of errors committed. (5) Unanticipated problems.

Figure 1

## Work Load Assessment Screen

Help	Communications	Science Procedures	Return
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2:54 AM**Work Load Assessment**

The Scenario has been completed. Please click on the three workload scales given below and assess the degree of effort you had to expend to accomplish all tasks in the scenario.

Physical Effort	<input type="text"/>
Mental Effort	<input type="text"/>
Total Effort	<input type="text"/>

Click here when assessment is completed:

Completed

Regarding the assessment of errors, each expert kept track of the number and kinds of errors that were committed during each scenario. An error was defined in relation to "nominal or expected" performance by each subject on each scenario. The expert observed each subject's activities (remotely) throughout the familiarization/training runs in order to develop a general concept of what was considered "nominal or expected" performance during later data runs. The test subject, ground controller, and PI also made written note(s) of unanticipated problems which occurred.

*Task Accomplishment Time.* A computer monitored the amount of time required by the subject to finish each step during each scenario. These times, in seconds, were stored and then printed out following each scenario for later analysis.

**Apparatus:**

The test hardware used can best be described in terms of the three remotely located laboratory areas and the hardware each contained: Control Monitoring Area, Glovebox Area, Ground Expert Area. Figure 2 is a diagram of all three areas approximately to scale showing the various video components used in this test. Figure 3 is a schematic diagram of all of the audio communication hardware that was used.

**1. Control/Monitoring Area.** The ground control station was located in a floor area approximately 8 by 10 feet which is shown in Figure 4. A large screen (29") high resolution color TV monitor (left) was used to display the output from any of the six closed circuit cameras to the ground controller. Cameras 1 - 3 were situated inside the glovebox (as will be described) while camera 4 was located across the Space Station aisle on top of the Element Control Workstation described below. Two more cameras were located at the Ground Expert's area.

Figure 2

## Video Hardware and General Equipment Layout

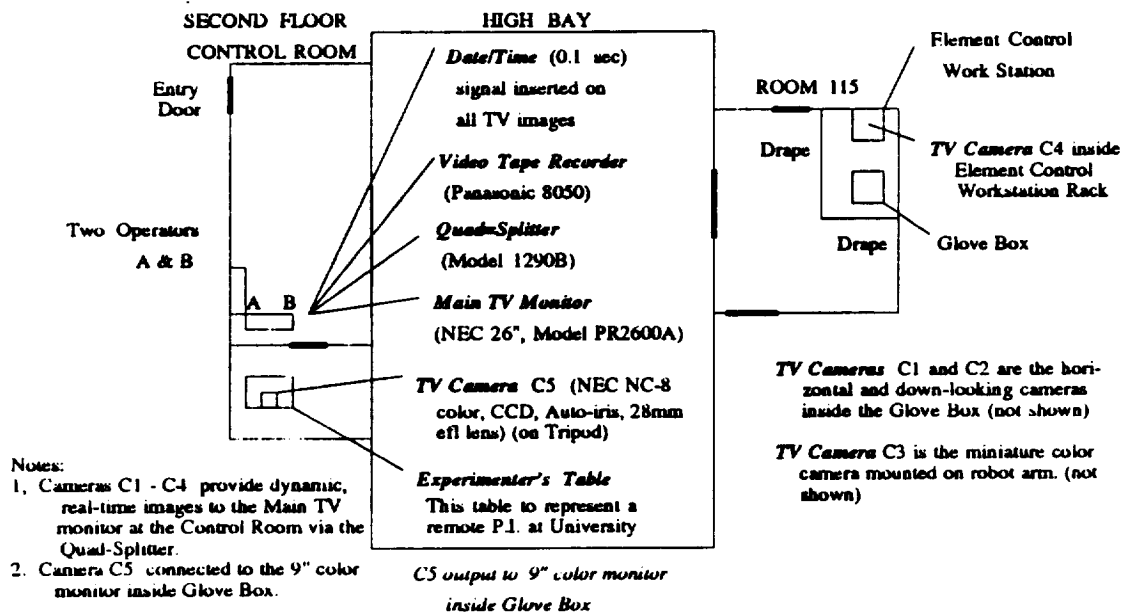


Figure 3

## Audio Hardware and General Equipment Layout

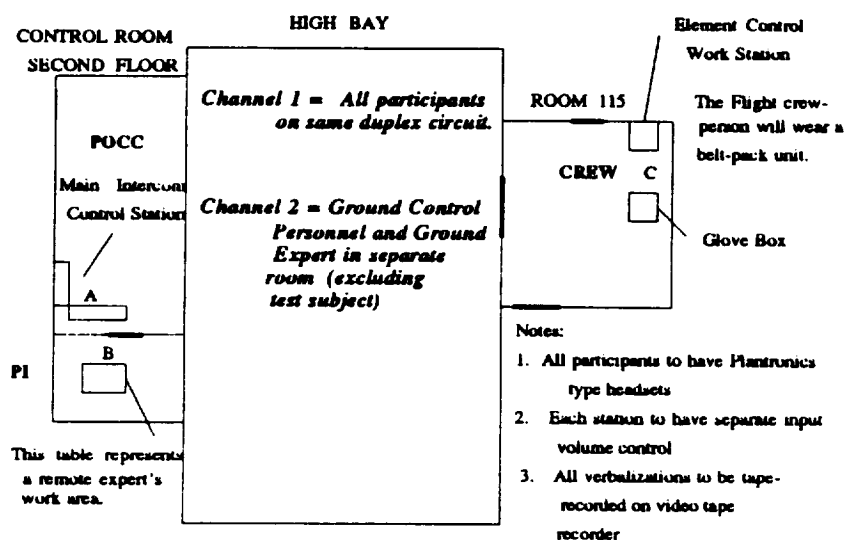


Figure 4

## Photograph of Ground Control Work Area

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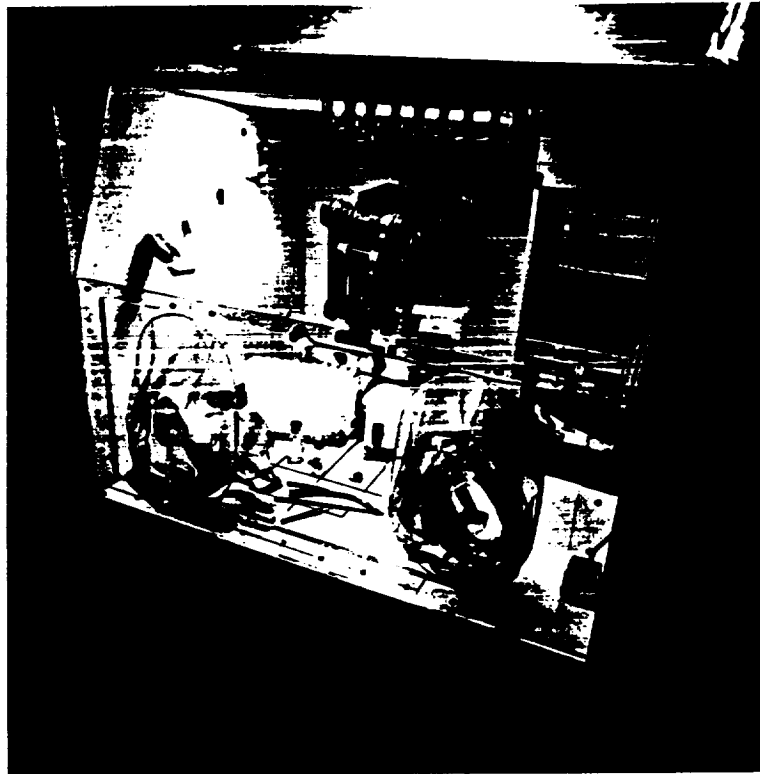


The large format TV monitor displayed digital date and time (one second accuracy) and its imagery was recorded continuously on a timelapse VHS video cassette recorder (Javelin, model XL 1000) for later analysis. The reason for using a large format quad-image display and a second 19 inch single scene monitor (showing the entire glovebox from across the aisle) was to provide the ground controller with enhanced situational awareness of all activities within and around the glove box and to be better able to evaluate what are the most effective camera views to monitor all aspects of the operations. A video switching network was used which allowed the image from any camera to be displayed on any monitor.

**2. Glovebox.** The glovebox consisted of a vertically standing, plywood enclosed, aluminum frame (Space Station double-wide rack) structure with a transparent upper front section. During normal operation the user inserts sealed containers into the lower "entry vestibule", closes the front door, and then slides the "inner vestibule door" open to remove the container or its contents. Figure 5 shows this structure. Its front face is 71.5 inches high by 39.5 inches wide. Its overall depth is 36 inches. The glovebox contained a number of items which included: (1) Macintosh computer with mouse input control (i.e., no keyboard was used), (2) high resolution 9" color TV monitor (NEC, model PM-971A), (3) programmable robot (SCORBOT), (4) miniature color CCD TV camera (Toshiba, Model IK-M30) attached to the robot's wrist, (5) two tube, 20-watt, ceiling-mounted cool white fluorescent fixture, and (6) front panel power controls.

Figure 5

## Photograph of the Glove Box



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Three small color TV cameras were mounted inside the glovebox. Two were Panasonic model WV-CD-132 CCD cameras with 8 mm f1:1.4 fixed focus lenses. One of these was mounted above the ceiling of the glovebox aimed vertically downward with its optical axis approximately centered on the inside floor of the glovebox. The second was mounted outside the glovebox on the right wall and aimed horizontally at the inside left wall. Its optical axis was approximately five inches above the floor of the glovebox so that it imaged a conical region measuring about 26 inches diameter on the left wall and covering most of the floor. The depth of field of both cameras was from approximately 12 to 25 inches. The third CCD color camera was a Toshiba model IK-M30A with 7.5 mm f1:1.6 fixed focus lens. This ultra-miniature camera was rigidly attached to the jaw support wrist bracket of the robot so that it would capture the pincer motion and X-Y-Y motions without introducing any visual field rotations which were found to be highly disorienting. Its conical field of view subtended a half-angle of approximately 13 degrees arc.

The lower right front of the glovebox contained a power control panel with the following (PRESS-ON, PRESS-OFF) lighted switches (top to bottom): Lights, Air Supply, Vacuum, Downlooking Camera, Sidelooking Camera, Robot Arm Camera, Main Power, CRT Power, Robot Power, Computer Power, Spare, Spare. The power-up/check-out procedure required the subject to activate certain of these switches at various times.

Located directly across the Space Station center aisle was another rack referred to as the Element Control Workstation (Cohen, 1988). A Panasonic model WV-CD110A color VT camera with wide angle 10 mm f1:1.6 Switar fixed focus lens was installed so that it pointed at the glovebox assembly. This image was displayed continuously in the control/monitoring area to provide the controller with situational awareness within the entire area surrounding the glovebox.

For protocol A, the robot was programmed to carry out a series of autonomous macro-movements; each one was a movement related to fluid transfer in microgravity, e.g., (a) grasp a syringe located in a holding fixture at location X, (b) rotate/unlock syringe, (c) withdraw syringe from fixture, (d) translate syringe to a second Hoaglands solution dispensing fixture, (e) insert, rotate, and lock syringe in place, (f) fill syringe with (imaginary) fluid, etc. The participant's task was merely to monitor these movements and ensure that they were conducted properly and safely. Details of this software and hardware will be presented in a separate paper.

**3. Ground Expert Area.** The ground expert represented a person at a university who was integrally involved in the flight experiment (e.g., as its principal investigator). One of his duties was to provide, step-by-step instructions to the flight crewperson in order to carry out the required tasks. This individual also provided trouble-shooting assistance in the event of hardware failure or clarification in ambiguous situations. The expert completed the workload ratings after each scenario along with the subject. This ground expert's work area is shown in Figure 6.

Referring to Figure 6, two 21" medium resolution color monitors were placed side by side (to help reduce total eye scan distance). A Mac II microcomputer (right side) presented the procedural steps which all parties followed. Its keyboard was not used during data collection. An intercom with head-mounted microphone was also used by all participants. A clear flat workspace measuring 36" wide by 16" deep was maintained directly in front of the ground expert. Aimed down at the workspace was a readily moveable, miniature, color TV camera (Toshiba, model IK-M30A). Its imaged could be displayed on any monitor. A second CCD color TV camera with wider field of view was installed above the entire ground expert area. It provided overall situational awareness for others. Its image was rotated to correspond to the vantage angle of the miniature camera so that no mental image rotation was necessary. This was found to aid all participants in relating the two images to one another rapidly.

#### ***Procedure:***

**Training.** Each of the eight flight crewpersons was carefully trained in the correct conduct of the three experimental science protocols during their first four hour-long training period. Each became familiar with all equipment so that he or she felt comfortable with the displays and controls. Carefully planned motivational procedures became an important consideration. While a sufficient number of repeated sessions had to be run to ensure that asymptotic performance would be achieved, there was the possibility that loss of interest/boredom would ensue so that by the time the last "critical" run was accomplished performance would no longer be asymptotic. The following motivational techniques were employed to try to compensate for this unwanted effect.

Figure 6

Photograph of Ground Expert's Work Area



First, each participating mission specialist was treated individually and as a professional. The importance of this approach cannot be overemphasized. Indeed, each participant was a scientist or an engineer at NASA Ames. Each was expected to have a basic understanding of the overall test objectives as described in written materials provided to them before testing began. Second, each was trained by the same ground support team, i.e., ground personnel were never switched throughout data collection. This helped to strengthen the interpersonal ties and friendships which tend to develop during such testing. Indeed, in many cases the volunteer and ground communicator were on first-name basis as occurs in NASA flights. Third, each volunteer's performance was monitored closely so that, if there was any indication of changes, verbal encouragements could be given immediately and naturally.

It was important during training to emphasize the importance of staying on an approximate time schedule in order to make the automatically timed procedural steps more consistent from run to run and to maximize the amount of data collected. Each participant was told, *"It is very important for you to carry out each procedural step in a timely way. Do not waste time or wait excessively long between steps."*

*Testing Schedule.* Each participant spent two separate four hour-long sessions separated by one day. An AM session participant was always retested on his second test day in the AM (similarly for a PM subject) to help reduce circadian-induced performance effects.

Testing occurred four days during each week, allowing the fifth day for maintenance, data collation, and analysis. Specific procedural events administered to each participant are described next.

The participant was greeted and asked to read and sign an informed consent form (Appendix B). He was then given a verbal explanation of the study, its goals and objectives, the apparatus to be used, and provided an opportunity to ask questions. This was followed by actual hands-on demonstrations of: the audio communication system, the video camera and glovebox power controls, insertion of the hands into the rubber gloves, use of the computer mouse control inside the glovebox and computerized subjective workload rating procedures, the stowage compartment contents and related procedures. Science protocol practice sessions followed in groups of three. The next activity was a real-time demonstration of the three protocols in the order (A), (B), (C). Each protocol required a different amount of time and different skills. Appendix C presents the individual steps of each protocol. Protocol (A) refers to "*Seed Germinator Charging*", (B) refers to "*Plant Sample Acquisition and Preservation*," and (C) to "*Remote Plant Observation*."

During the first day's training session each protocol was practiced twice as shown in Table 1. Four participants received no video mode at all, i.e., the color monitor inside the glovebox was turned off throughout all familiarization, training, warm-ups, and data collection runs. Their performance was compared with the performance of the four subjects who did have this form of telecommunications information. In addition, the monitors at the ground control and PI sites were also turned off in order to evaluate their contribution to the PI's and ground controller's ability to carry out the required operations.

Since protocol (A) required about 9 minutes to complete, (B) required about 18 minutes, and (C) required about 9 minutes, after training, a total of three groups of the three protocols (i.e., nine total) were completed by the end of the second day. The first group served as general familiarization and warm-up even though data was collected. This approach was taken in order to try to get the participant's performance level at or near asymptote as quickly as possible.

The second test session began at the same start time as the first test session but one day later. Participant 1 was then given protocols: (A)(B)(C) (cf. Table 1); followed immediately by protocols (B)(C)(A) and then (C)(A)(B) with a ten-minute rest period separating each group. During the third and final group of protocols, (for example (C)(A)(B) for subject 1) one of four carefully pre-planned telescience failures took place. They are discussed in detail below.

*Unique Failure Runs.* A unique and different type of telescience mode failure was inserted unobtrusively by an experimenter during the last scenario to each subject (cf. Table 1, last bold-faced letter in each row); the flight crewperson did not realize it would happen.



Table 1

## Test Scenario Presentation Order

COMPUTER IN GLOVEBOX		VIDEO		Training Sessions		Data Collection Sessions		Unique Failure Run	
SUBJECTS	ON	1	ON	P-A-B-C <sub>1</sub>	A-C-B <sub>2</sub>	A-B-C <sub>3</sub>	B-C-A <sub>4</sub>	C-A-B <sub>5</sub>	V
		2	OFF	B-A-C <sub>6</sub>	C-B-A <sub>7</sub>	C-B-A <sub>8</sub>	A-C-B <sub>9</sub>	B-A-C <sub>10</sub>	A
		3	ON	C-A-B <sub>11</sub>	C-B-A <sub>12</sub>	A-B-C <sub>13</sub>	B-C-A <sub>14</sub>	C-A-B <sub>15</sub>	W
		4	OFF	A-C-B <sub>16</sub>	B-C-A <sub>17</sub>	C-A-B <sub>18</sub>	A-B-C <sub>19</sub>	B-C-A <sub>20</sub>	C
SUBJECTS	OFF	5	ON	C-B-A <sub>21</sub>	C-A-B <sub>22</sub>	C-B-A <sub>23</sub>	B-A-C <sub>24</sub>	A-C-B <sub>25</sub>	V
		6	OFF	A-B-C <sub>26</sub>	C-A-B <sub>27</sub>	B-C-A <sub>28</sub>	C-A-B <sub>29</sub>	A-B-C <sub>30</sub>	A
		7	ON	B-C-A <sub>31</sub>	B-A-C <sub>32</sub>	B-A-C <sub>33</sub>	C-B-A <sub>34</sub>	A-C-B <sub>35</sub>	V
		8	OFF	B-A-C <sub>36</sub>	C-B-A <sub>37</sub>	B-A-C <sub>38</sub>	A-C-B <sub>39</sub>	C-B-A <sub>40</sub>	C

Unique Failure Run Key: V = Video, A = Audio, W = Workstation, C = Collaboration

(1) **Video Failure.** During this type of failure the ground controller announced that, "a power failure had caused the TV monitor inside the glovebox to fail. All operations should be continued on a "best performance basis". The failure always occurred just prior to conduct of protocol (B) "Plant Sample Acquisition and Preservation." Likewise, all video downlinks from the glovebox to the ground expert PI also were turned off so that only a voice link and digital (computer screen) link remained.

Of primary interest was the impact this failure would have on the ability of all participants: (a) to successfully conduct the protocol. (b) What kind of response(s) was made? (c) How long did it take to reach a decision for each of the two groups (i.e., the four subjects previously trained to carry out the scenario without video support versus the other four who had trained using video), and (d) on their workload ratings.

(2) **Audio Failure.** When this type of failure occurred it was always during the last scenario. Ground control did not announce that a failure would occur. This event occurred about 30 seconds into protocol (C) "Remote Plant Diagnosis" and the flight crewperson had to adopt alternative methods of communicating, terminate the protocol, or continue on an unauthorized basis. When the experimental design permitted its use, all parties could use an electronic mail system to communicate if they desired. If a subject did communicate using the electronic mail and asked for instructions he or she was told, "we have had an audio system failure, proceed on a "best effort" basis."

Of particular interest was: (a) what type of response(s) were made, (b) how long it took to execute it (them), (c) the adequacy of the response, (d) were other available telescience modes used? (e) the number and type of performance errors this failure produced, and (f) the impact on their workload ratings.

(3) **Workstation Presentation Failure.** This failure consisted of unexpectedly presenting garbled screen information for procedural steps 12 and 16 of protocol B "Plant Sample Acquisition and Preservation" since it had the largest number of individual steps. It was reasoned that the participant would have most difficulty remembering all of these steps and would tend to rely more on the screen display as a step-by-step cue. It always occurred during the last scenario of the experiment.

This failure always occurred in step 12 which was supposed to state (on the monitor screen): *"Position all items so that the inner airlock door can be opened"*, and again about one minute later on step 16 which was supposed to state, *"Wipe down the glovebox with wet wipes and bag for trash."* It was reasoned that these steps had been practiced many times before (i.e., during previous practice and data runs) and the participant may simply know what to do without prompting. On the other hand, the participant may wait for ground control to give another (ungarbled) go-ahead for this step. These subjects never waited for a go-ahead during this failure.

When the "critical" step appeared in unintelligible form (i.e., random letters) on the screen it was of interest to find out: (a) what initial response was made, (b) how long did it take to find an acceptable solution to the problem (e.g., by asking the ground controller to read it to them, to recall it from memory and have ground control verify its accuracy), (c) did they use another available telescience mode to work around the error, (d) the number and types of errors made, (e) what unanticipated problems were encountered, (f) task accomplishment time, and (g) the impact on their workload ratings.

(4) **Collaboration Failure.** This failure was produced by having the ground controller simply not respond to the flight crewperson for a period of three (3) minutes. It always occurred during the last scenario and at a time when the ground controller should have been available, viz., at the start of step 10 of protocol A "Seed Germinator Charging." This step prompts the flight crewperson to *"Click SEND to send a message to the POCC to prepare for monitoring. Advance only after the POCC acknowledges the message."* It was of interest to find out (a) how long the participant would wait for the ground support person to return, (b) whether they would simply ignore the lack of ground response and go ahead anyway, or take some other action (e.g., wait out the three minute-long period), (c) whether any (other) available telescience mode would be used and when, (d) the number and type of performance errors this event caused, (e) whether unanticipated problems would be caused by this failure, and (f) the impact on their workload rating.

If the crewperson challenged the ground controller about what happened, the following response was always given after the failure period. *"We're sorry (name of participant), we had a temporary communication glitch down here... hope it didn't get in your way."*

***Test Participants:***

Eight volunteers took part as surrogate spaceflight mission specialists. Four were male and four female. Their average age was 33.6 years. All were in good health and possessed 20:20 corrected or uncorrected vision. None was familiar with the three protocols. Three were biologists with some familiarity with a glovebox (bio-isolation chamber) and the procedures that are involved in using one. Four were engineers and one was a computer science major. This diversity of background helped us to assess what is involved in conducting crew coaching and training to people with different disciplinary backgrounds.

Since the basic objective of this test was to evaluate selected aspects of the telescience support system, the two experimental support team members were also considered as test subjects. The ground controller served as video system switcher when the PI or flight crew person requested different camera views. He also coordinated the test runs to ensure that the correct test schedule was followed and monitored overall quality of science being performed. The ground expert [also referred to as the principal investigator (PI)] played the part of a university scientist whose experiment was being carried out in space. He gave visual and voice coaching and prompts as needed.

Two persons acted as expert raters throughout data collection. Each monitored the performance of the test subject as well as the two support team members. One rater had primary responsibility for monitoring the hardware and software operations during the data collection. The other rater observed the behavior of the subject, ground controller, and PI and also watched for system inadequacies.

## RESULTS

The results are presented in the following sections: (1) Impact of Telescience on Productivity, (2) Impact of Telescience on Task Accomplishment Time, (3) Impact of Telescience on Dealing With Errors, (4) Capability of Using Telescience to Cope with Off Nominal Events, (5) Glovebox Hardware/Software Redesign Comments, and (6) General Comments.

In general, this experiment explored the general usefulness of three telescience modes of information presentation upon remote coaching of fairly complex scientific procedures. The ability to show the subject exactly how to carry out these procedures was significantly enhanced by having a high resolution color monitor located where it could be seen at all times (inside the glove box) and simultaneous audio transmission. Nevertheless, the audio channel was considered to be the most critically important channel of the three tested. As is noted below, some subjects disregarded the computer-driven procedures checklist during audio-visual coaching.

### (1) Impact of Telescience on Productivity

### Savings in Crew Time Results

The following comments were made by the subjects during a group debriefing after the study. With regard to the workstation's "electronic" check list one subject said, "I paid attention to the check list only the first time. Later I ignored it. I just went through the motions (to satisfy the requirements of the experimenter). For example, I checked off the seed germinator even though it was still attached to the side wall of the glove box." Another subject remarked, "I liked the check list and would want to have a verbal command capability (to activate each item). To be able to step through it would permit me to switch off one level of consciousness." Another subject said, "I liked the video (inside the glove box) at first but later I found it constraining, like a Big Brother type thing." Another subject felt that the experimenters, who were also following identical check lists slowed him down in accomplishing the required tasks. The ground controller relied on the checklist throughout the entire study since he was constantly being distracted by outside, ongoing requests for assistance which drew his attention away from the ongoing science procedures. Having the real time checklist always available was a big help to him. The PI remarked, "My check list on the monitor may have slowed me down but it was really a help."

### Savings in Ground Controller and PI Time

Having a video image to show exactly what the subject was doing during these science procedures proved to be extremely important. The ground controller estimated that he saved at least five minutes per procedure by not having to look up printed procedural steps in a manual. For the fifteen different scenarios completed by each subject this savings adds up to one hour and fifteen minutes. The PI did not have specific comments on this subject.

### Quality of Science Rating Results

In general, the availability of audio, visual, and computer workstation information resulted in improved science quality. However, individual differences among these subjects qualified this conclusion. Some subjects with a biology background did not rely as heavily on the available telescience modes as did subjects who were not familiar with the hardware and procedures. In other words the telescience support helped compensate for deficiencies in a subject's science background.

Referring to Table 1, the first four subjects were trained with and always had video imagery available inside the glove box. This high resolution color view could be switched from one camera to another upon (verbal) command to the POCC. These four subjects tended to perform required tasks with greater precision and "rigidity", i.e., their performance tended to be better than the four subjects who had never had the benefit of video imagery. Both the PI and expert raters agreed on this. This tended to be true even for those subjects with very positive attitudes toward the experiment. As might be expected, those subjects with prior biological research experience performed the tasks more precisely than did the non-biologists despite the array of telescience support hardware and software available. Only the expert raters could assess quality of science during tests on the last four subjects since video was not available to the PI or to the ground controller. The expert raters indicated that vid-

eo definitely contributed to higher quality of science because: (1) The PI could immediately assist the subject in preventing incorrect actions. An example of this occurred during a no video run when a non-biologist subject literally crushed a plant root into a cryo-stub prior to snap freezing. If this had happened in space the PI would not have known about the ruined sample until it was returned to Earth, (2) The PI could physically demonstrate a new task from one or more visual vantage points for a subject prior to its accomplishment, (3) The PI could tell when a procedure was over and could move immediately to the next task without the subject having to inform him that it was over, and (4) The subject was less free to exercise personal freedom in how a procedure was carried out when he or she knew the procedure was being watched by others who might correct them in public.

The following comments were made by the subjects during the post-test debriefing: (1) "The video was very important during training. I liked to be able to see the PI's face (personal identity and expressions), however, the actual flight crew may not like the rear view camera (located at the element control workstation rack opposite the glove box) yet it may lead to better science," (2) "Let the crew understand that they are part of a team and give them mutual respect and support. Get a dialog going with them," (3) One of the engineer test subjects said, "How should we decide which (plant) sample to keep and which to throw out? The video led to my achieving better quality of science," (4) Another subject commented, "...I verbalized each step out loud (while reading it off the glove box monitor)," and (5) The PI felt that he wanted "...all available telescience modes available all of the time."

The PI stated that, "The most important factor that influenced the quality of science was the two-way video. The video was essential for procedure verification, coaching by a ground expert, and coping with off nominal events."

He continued, "Many of the procedures that the crew must carry out involve preservation of plant and animal tissues. Many of these techniques are highly specialized for a given discipline and are very difficult to complete correctly. They are all or nothing propositions. If a small mistake is made the sample is lost. Having a ground expert observe the procedure from many angles made it possible for mistakes to be caught while there was still time to do the procedure correctly. During parts of the test where the video was shut off, the narrative from the crew indicated that the procedure was being completed correctly, but after review of the video tapes it was found that many mistakes were made that would have resulted in the loss of the experiment. During the course of a 180 day flight, many off nominal events (probably) will occur that the crew will have to cope with. They cannot be trained to cope with every contingency of every life science (or other) discipline. Video coaching will allow a discipline expert, who best knows the objective of the experiment, to cope with the off nominal event." Still another consideration is that of shared responsibility; the present type of telescience support for mutual, real time collaboration essentially distributes the liability for failed science procedures more broadly (and evenly) among all participants.

The PI also remarked after the study that the greater the video exposure a subject had the more confidence he or she seemed to have toward the accomplishment of a given science procedure during an off nominal run.

### Subjective Workload Rating Results

A total of 1020 separate workload ratings were made in this study, 480 by the ground controller, 480 by the PI, and 60 by each of the eight subjects. Two-way mixed model analyses of variance were performed with video on/off as one dimension and workstation on/off as the second for the three workload measures used as well as the three test scenarios. These findings across all test subjects are presented in Table 2.

Table 2

Statistically Significant Analysis of Variance  
Results for Mean Subjective Workload Results  
(P value cited)

Workload Scale	Test Procedure	Source of Error		
		Workstation (On/Off)	Video (On/Off)	Workstation x Video Interaction
Mental	A	---	---	0.0006
	B	---	---	0.0001
	C	---	---	0.0001
Physical	A	---	0.044	0.007
	B	---	---	0.015
	C	---	0.013	0.001
Total	A	---	0.048	0.0004
	B	---	---	0.002
	C	---	---	0.002

When plotted, these significant two-way interactions for physical effort were the result of the fact that mean workload decreased from the video off to video on condition when the workstation was on and increased when the workstation was off. This finding not only suggests that the two telescience information sources complement one another by decreasing physical workload when both are on but also that the video information played a more powerful role than did the workstation.

### Flexibility of Scheduling Results

It was discovered that the present three node telescience support system did not contribute significantly to an increase in scheduling flexibility. This may be due to the fact that the experimental design called for a rigid activity schedule by all three participant groups. A subject remarked during his post-test debriefing that, "he would use on-board video tapes of planned procedures and supplement them with ad lib coaching where necessary."

## Transaction Management Results

The management of all science related transactions will assume increasing importance as the number of experiments to be carried out increases and the time available to conduct them diminishes. The proper use of telescience related procedures and hardware should positively impact this management role.

It was found that the video off test condition was very boring for both the PI and the ground controller and tended to lead to increased environmental distractions and missed procedural steps. In general, the fewer number of procedural steps to carry out the faster the subject got bored. More errors tended to be made as boredom level increased. The level of verbal interchange between the subject and the PI and ground controller also increased. A subject remarked, "It is far fetched to anticipate on-orbit astronaut training, particularly with the limited bandwidth that will probably exist to and from Earth... (such training) will pose a significant procedural problem."

## (2) Impact of Telescience on Task Accomplishment Time

### Time Line Analysis Results

A computer logged the elapsed time of each mouse click made by all three participants (subjects, ground controller, PI). This was done to obtain data on typical time to accomplish the various tasks; task performance time is useful in planning for training, etc. Figures 7 - 9 present total time to accomplish scenarios A - C, respectively by each subject. The filled circles are for the unique failure run which *always* resulted in the longest accomplishment times.

Procedure elapsed time averaged across the three scenarios and all eight subjects ranged from 7.3 to 27.1 minutes for the first data collection period on the test day, from 4.6 to 23.6 minutes for the second data collection period, and from 5.8 to 25.2 minutes for third and final data collection period. There was no pronounced reduction in task accomplishment time suggesting that these subjects had already reached stable task accomplishment times by the test day. This may also support the general observation that these subjects required only one training day to attain relatively stable task accomplishment time and proficiency.

The electronic checklist inside the glove box proved to be a useful and popular source of information for the subject. Having future required procedural steps visible made it possible to carry them out in a more relaxed, flexible, and continuous manner. In this regard a subject commented, "I found myself checking and carrying out present and future activity steps and then clicking the mouse to indicate I had completed them as the instructions required."

Figure 7

Performance Elapsed Time by Subject  
for Scenario A

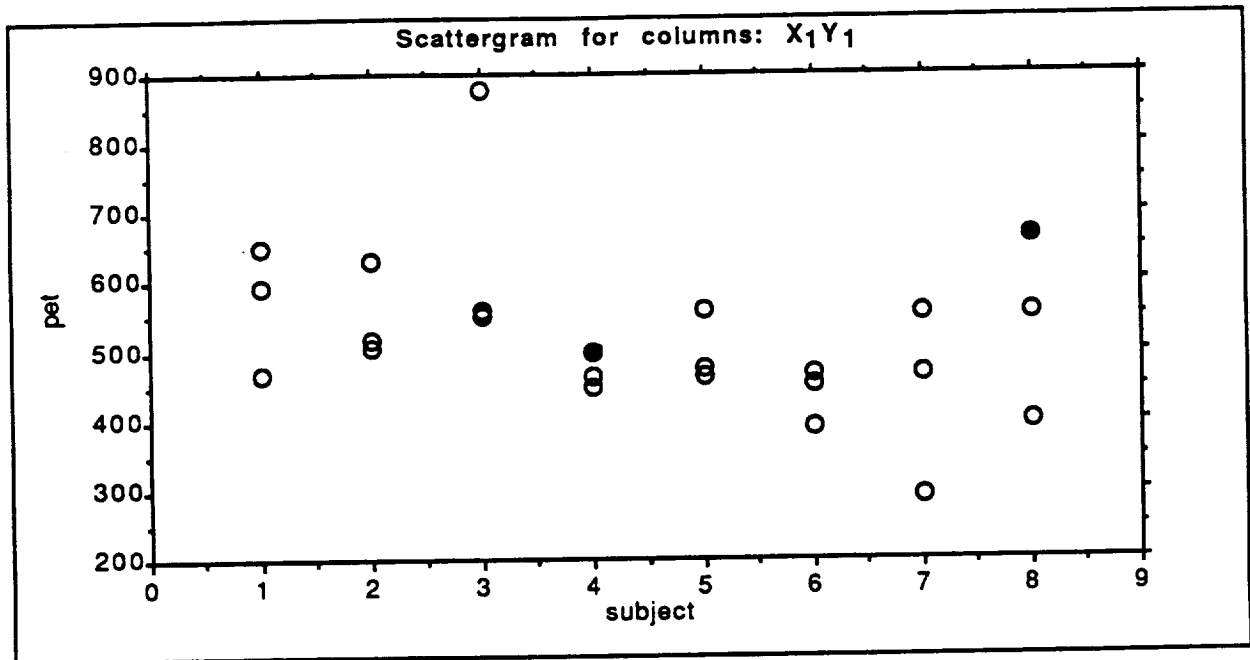


Figure 8

Performance Elapsed Time by Subject  
for Scenario B

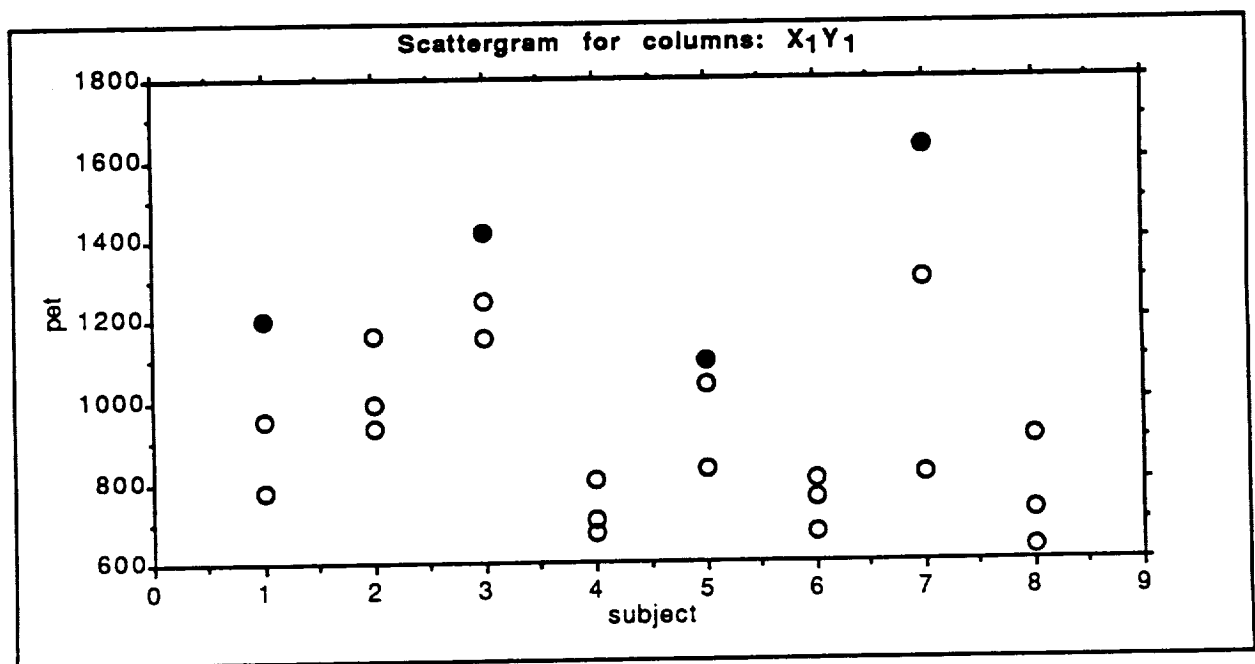
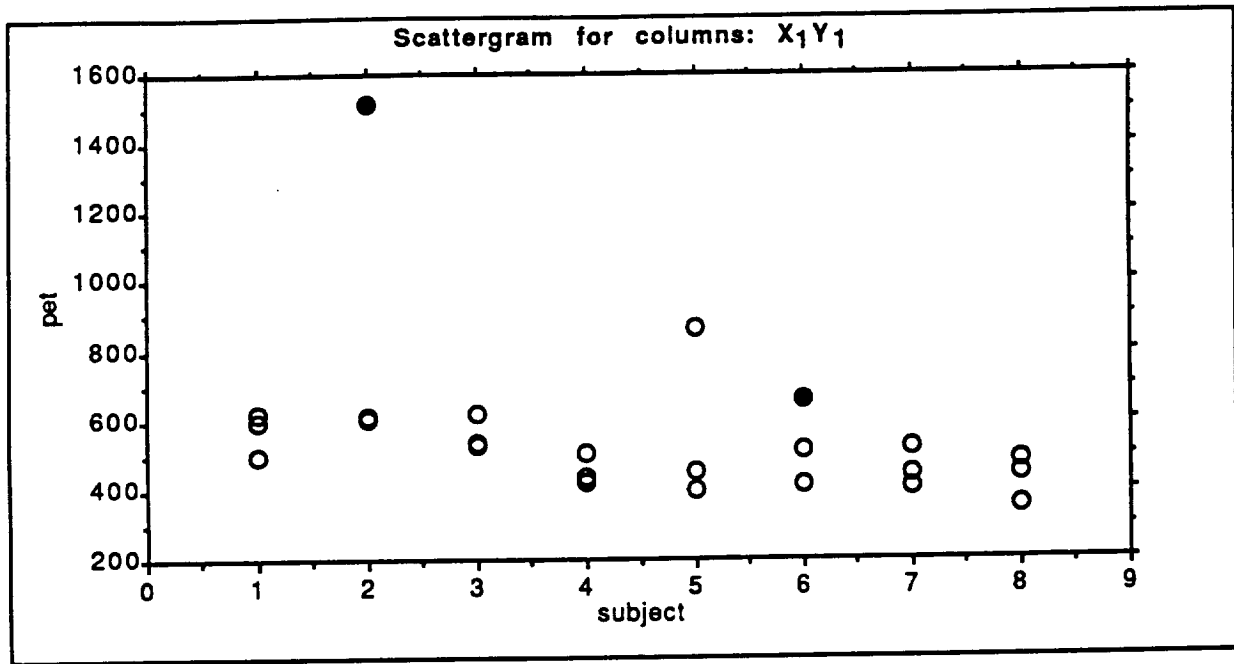




Figure 9

Performance Elapsed Time by Subject  
for Scenario C



Use of an automated checklist displayed inside the glove box may be more useful when one is learning new procedures than it would be later, particularly for simple experimental protocols. Most of the subjects learned the procedures so thoroughly by the second day that they didn't have to refer to the checklist very often and several claimed that it slowed them down. Using "flexible software" that can be readily modified over the course of a mission to match the current (and changing) requirements of each subject may well be a better approach and should be evaluated experimentally.

Several subjects remarked about the presence and use of a rudimentary robot inside the glove box. It must be noted that this study was not designed to evaluate robotic operations; the robot and control system was included to demonstrate several basic fluid handling procedures that had been developed earlier (Schooley et al., 1989). During the post-test debriefing one test subject said, "The robot seemed like a useless procedure, i.e., doing a variety of tasks OK rather than one task perfectly." Another subject remarked, "I would rather be my own robot on limited numbers of repetitive procedures."

The ground controller found the computer check list to be very useful in keeping him in step with the ground controller and PI. However, when the subject forgot to click on an item the controller's workload increased since he had to remind the subject to make the necessary response(s). This happened about five percent of the time.

Total mean elapsed time to complete scenario B with video on was 18.7 minutes and only 13.5 minutes with video off (across both workstation states) ( $F = 12$ ;  $df = 1$ ;  $P = 0.002$ ). While the video on condition tended to slow down procedure accomplishment time the overall quality of science carried out was far higher (see discussions in sections 1 and 3).

### (3) Impact of Telescience on Dealing With Errors

#### Error Analysis Results

The potential always exists for human errors to be made during long, complex, and repetitive manned procedures (Meister, 1982). There are errors of omission and commission which range in severity from innocuous to disastrous. A number of types of errors were identified in this experiment which illustrated the importance of having a television monitoring capability for ground-based personnel to monitor crew performance remotely. Having a communication link between the ground and on-orbit personnel made it possible to monitor performance and behavior more consistently. This is illustrated by a comment made by the PI after the test. He said, "The crew said they were doing the procedure one way but were actually doing it another. My TV gave me immediate insights about this."

The PI continued, "The loss of video resulted in many errors committed by the crew that were not caught by the ground PI. Most of these errors would have resulted in the loss of the tissue sample, and some would have resulted in a safety hazard and/or injury to the crew. Undetected errors included poisonous glutaraldehyde fixative spills, broken bioisolation between the crew and specimens, frostbite of a crew's fingers, too much time between tissue removal and freezing and fixation, mechanical damage of samples, incorrect cryo freezer operation, incorrect positioning of a plant for an infrared scan, and incorrect descriptions of plant pathology. As has been described above, the video view for the ground expert is necessary to catch mistakes as they happen so that the procedure can be repeated if necessary. Audio narrative by the crew made it sound like everything was going fine when it was not. The loss of the electronic checklist also caused the crew to skip steps and to lose their place in the experiment several times."

A detailed analysis of the post-test video tapes showed that there were sixteen major procedural errors committed across the four subjects to whom video was not available during their 5.4 hours of total testing. There is every reason to believe that most or all of these errors would have been caught if real time video coverage had been available.

The expert raters commented on a number of errors which took place. They noted: (1) Inadvertent activation of audio buttons and screen (icon) buttons. Both the ground controller and PI made incorrect manual responses to screen icon buttons when the subject did not respond quickly enough. It was as if they were trying to respond in place of the subject to keep the experimental procedures moving along. (2) On several occasions the macintosh software failed to proceed through the full list of checklist items and had to be rebooted. (3) When the printer was operating it inhibited use of the macintosh. This delayed the start of a scenario several times by about five minutes. (4) Sometimes several subjects would finish

two or more consecutive steps in a scenario before clicking the mouse on them. This was done primarily during the use of equipment gathering and stowage checklists where many items had to be identified and moved to another location. The subject was told that they could click off all of the items *after* all of the items had been correctly moved. While making their tasks smoother, this kind of response "error" made the automated timing of each successive step in error to some degree. In several instances two subjects clicked off all items during a post-test stowage activity even though a major piece of equipment was still inside the glovebox and in full view! Since it was velcro-attached to a side wall and not lying on the bottom surface of the glove box with the rest of the equipment, it was overlooked. (5) The on-screen command buttons to activate the robot in scenario A were sometimes used incorrectly leading to lost time when the software had to be reinitialized. Later in the experiment when this occurred the team simply went on, disregarding the consequences. (6) The ground controller inadvertently left the microphone on several times while he discussed experimental details with the PI and others present. The subject overheard this conversation with unknown consequences. A "hot mike" panel light would have helped reduce this possibility. (7) On several occasions the subject did not wait for the proper acknowledgement before initiating the robot motion in scenario A.

### Unanticipated Problems

A number of unanticipated problems occurred during this experiment. They included: (1) Differences in terminology/names used by all three participants for some of the objects used to carry out a scientific procedure. For example, the inner glove box door was actually a horizontally sliding surface and was confused on occasion with the outer vestibule door. This kind of confusion was infrequent, however. At times a subject would merely point at something to identify it knowing that someone probably would be watching and could identify it. (2) A TV camera was incorrectly aimed during one run so that a desired scene was not achieved. This problem probably arose from an inadvertent bump of the camera between tests and the fact that camera view checks were not made prior to testing each day. (3) A time lag of approximately eight seconds occurred (due to computer processing time) between the time the subject made a mouse input to a check list and the time both the PI's and the ground controller's computer screen accurately reflected their mouse input. This delay led to some coordination problems early in the study until the nature of the problem was determined. Thereafter appropriate allowances were made to resynchronize all participants. These usually took the form of the ground controller announcing over the intercom that there was a transmission delay and not to initiate a following step until all screens were synchronized. The subject acknowledged this verbally. (4) A discussion held between the PI and ground controller dealing with the interpretation of a particular instruction was overheard by the subject with unknown consequences. (5) As the subject became more and more familiar with the instructions he or she would carry out procedural steps without looking at the computer check list at all. In several instances the wrong procedure was carried out. (6) One subject accidentally cut his finger with the scalpel. While there was almost no blood loss he did have to stop the procedure to deal with it. Future bioisolation facilities must take this kind of accident into account and provide for immediate, self-actualized first aid. (7) During scenario B the subject accidentally pulled the stopper out of the glutaraldehyde bottle. If it had

actually been filled, this highly caustic fluid would have spread throughout the glove box causing various problems (sample and equipment contamination, electrical shorting, TV camera lens coating, etc.). The subject mentioned the spill almost immediately. Both the PI and the ground controller also saw it happen and were ready to verbally assist the subject in the clean-up procedures which had to be carried out. Training was *not* provided for such clean up procedures prior to testing. This accident slowed the procedure's completion by about three minutes and demonstrated the importance of performing procedurally correct simulations with realistic hardware.

#### (4) Capability of Using Telescience to Cope with Off-Nominal Events

##### Crew Performance Results

One of the objectives of this study was to assess the role played by video, audio, and computer workstations in coping with four different kinds of unexpected failures. Each type of failure is discussed separately. In general, when the communication system failed these subjects showed that they could still complete the tasks by turning to alternative telescience modes.

*Video System Failure.* It will be recalled that the video (TV) display inside the glove box, at the POCC, and at the PI's station *all failed simultaneously* during protocol B. This proved to be both advantageous and detrimental to different subjects. Several questions were of interest:

(1) What kind of responses were made? Interestingly, the PI had grown so accustomed to relying on the computerized checklist information that when it failed early in the study he did not have a hard-copy backup to refer to. He had to request assistance from the ground controller at this time which lengthened the time needed to accomplish the procedure. Nevertheless, the procedure was completed successfully. Most of the first four subjects who were trained using the video system simply relied on their memory to complete the required tasks, i.e., the failure (probably) occurred too late to measure anything of real importance here. From the ground controller's standpoint this failure did not significantly influence his task accomplishment due to the high degree of overlearning that had taken place by the time this failure had taken place.

(2) What type of responses were made? Subject 7 coped well. He simply progressed with the now familiar procedural steps and verbalized what he was doing to the PI. His high level of familiarity with the required steps made the loss of video a minor inconvenience at most. Most of the subjects waited for some clarification of the problem from the PI or POCC.

(3) How was performance affected? In general, the unexpected system failure did not significantly influence task accomplishment. Since it always occurred on the last scenario the subjects were already trained (and also motivated) to complete all required tasks.

One subject remarked, "...when my video went out I could do it (the procedure) my own way." This subject was not a plant biologist. Another subject commented, "It was a challenge intellectually when I had no video... I had to visualize the steps... This helped to reduce boredom."

*Audio System Failure.* Some questions raised here included:

- (1) What type of responses were made? In general, it was noted that the subjects were highly dependent upon the audio system. When it stopped working a variety of responses ensued. Subject 6 simply stopped and did nothing at all while subject 8 was very patient, expecting the procedure to continue even though communication was lost. We think that because the video system was less obtrusive than the audio, when the audio failed the subjects did not rely upon the video as much or as rapidly as they relied upon the audio when the video failed. This interpretation is only tentative and should be researched further.
- (2) How long did it take to carry out the required tasks? Task performance time did not lengthen noticeably during the audio failure condition as compared with the normal audio condition.
- (3) How adequate was the response? Most of the subjects simply continued on with their tasks despite the failure.
- (4) Were other telescience modes used? Several subjects tried to use hand signals over the TV system to communicate with the PI but soon gave up and went on with the task.

*Workstation Presentation Failure.* This unique failure run only occurred for subject 3 who happened to be a biologist. While it is unwise to draw conclusions from a single subject several observations were made. Some questions of interest here included:

- (1) What initial response was made? This subject simply shrugged and went on with the required tasks. She also inquired about what had happened and asked whether it would be fixed? In general, failure of the workstation did not cause the subject much more than inconvenience. When she forgot a step she simply asked for help from the PI. That is, the audio visual channels were relied upon for task accomplishment more than the workstations.
- (2) How long did it take to find an acceptable solution to the problem? This subject continued with the procedural steps almost immediately.
- (3) Was another available telescience mode used to correct the error? Yes, the audio channel was used by the subject to inquire about the nature and duration of the problem and to request detailed procedural advice from the PI.
- (4) What unanticipated problems were encountered? None.
- (6) What was the task accomplishment time? This failure added 5.5 minutes to the amount

of time needed to complete this scenario. Reference to Figure 7 (cf. upper most data point for subject 3) shows that mean accomplishment time for the other two scenarios was about 9.1 minutes while the failed workstation in scenario B required 14.6 minutes. By comparison, the range of task accomplishment times for the other seven subjects for this scenario (also carried out during the last data run) ranged from 10.4 to 20.8 minutes indicating that this subject's task accomplishment times were faster than the average to begin with.

(7) What impact was there on workload ratings? None. This subject's ratings did not change following this off-nominal run.

*Collaboration Failure.* This failure consisted of the ground controller not responding verbally to the subject for three minutes during scenario A (Seed Germinator Charging) at the point when the ground controller was supposed to authorize the subject to activate the robot's motions. Several questions were of interest in this situation. They included:

(1) How long did the subject wait for the ground support person to return? Subject four initiated the robot without authorization after waiting about one minute into the "silent" period. The other subject (no. 8) waited the full three minutes and did not initiate the robot at all. Personality and other individual differences seem to play a strong role here which available telescience communication modes may only modify slightly.

(2) What response would the subject make? See previous paragraph for specific details. In addition, neither of the two subjects involved tried to communicate with the POCC using the electronic mail system at the Element Control Workstation.

(3) What kinds of errors would be caused? None were noted, however, this may be because the robot was already pre-programmed to carry out a fixed series of operations which only needed to be initiated and then visually monitored.

(4) What unanticipated problems would be caused? None.

(5) What impact would this have on workload ratings? Neither subject's physical, mental, or total workload ratings changed following this unique failure run from values given during previous runs.

#### (5) Glovebox Hardware/Software Redesign Comments

While not a central aspect of the study, the present rapid prototyping activity did elicit a number of interesting comments regarding design improvements to the present glovebox mockup. The subjects' own comments are presented here in no particular order: (1) "Those items which are used in most or all of the procedures should be located inside the glove box itself, for instance the trash bags and wet wipes." (2) "The depth of the glovebox vestibule was too great. As I reached down into it with my gloves my microphone kept hitting the front glass." (3) "I didn't use the video very much on day 1 but (I) learned to appreciate it on

day 2. "I only needed the video in the beginning. Later I did ask for it to see down into the vestibule." (4) Several subjects commented on the value of being able to "click" the electronic checklist by a voice input. A subject remarked, "It may be important to be able to tailor the use and design of the check list." (5) One subject suggested that all glove box equipment that had to be installed and later stowed should be represented on the computer screen by their outline (shape). When they are clicked off (after being properly stowed) each outline should disappear. (6) On numerous occasions subjects would leave the inner vestibule door ajar as they opened the outer door. An interlock system must be installed to prevent this from happening in space. (7) One subject used the tiny condenser microphone mounted to the front of the glove box to scratch her nose on. Another (female) subject commented that her hair tickled her face when her hands were in the gloves and not available to deal with the situation.

The presence of the five-axis robot inside the glovebox prompted a number of comments, e.g., (1) "A robot will be useful on repetitive tasks and in carrying out operations in harsh environments." (2) "The robot should do the snap freezing operations." (3) "The robot took up a large volume for (giving) relatively little value. The crew still would need to monitor its activities rather than having the POCC do the monitoring." This comment raises the important issue of how *properly designed* telescience acts to redistribute the responsibility for operations monitoring. This may not be good since there is the possibility that all participants will reduce the amount of their active, deliberate monitoring because they (may) assume that another (remote and thus unseen) participant is doing so.

## (6) General Comments

An interesting comment made by an expert rater was that the various steps making up each test scenario are not of equal value from the standpoint of achieving high quality science. Indeed, some are far more important contributors to science quality than are others. Should the relative importance of one step versus another in a science procedure be indicated, particularly to the less experienced subject?

Several lessons were learned regarding control switching from one participant to another: (1) It was found to be very helpful to be able to switch TV camera views from the POCC rather than burden the subject or PI with this task. This switching was accomplished quickly (typically within several seconds after a request was made). It helped the PI to monitor the subject's performance in a time-efficient manner and the subject to have useful video information available when needed. It also prevented the subject from having a different camera view inside the glove box than what was being displayed to the PI, i.e., both views could be pre-set to be the same by the TV image controller. (2) The POCC was much faster and made fewer switching errors when the PI used a standardized numbering system for the cameras and monitors. (3) The audio system used was full duplex between all three nodes. During the no video trials neither the PI nor the ground controller could see the subject when he finished a procedure; both had to rely on the audio channel for this information. This resulted in some confusion while passing control from one participant to another which a half-duplex system would have obviated. It was felt that a full video system would not require a half-du-

plex system because of the immediate visual confirmation of activities that is possible.

This experiment demonstrated the value of being able to rapidly prototype different teleoperations-related information systems. Basic screen icons were "drawn" quickly using hypercard and evaluated from a human factors design standpoint prior to their inclusion in this study. (Johnson, in preparation) The location of displays and controls also could be varied at will since full scale cardboard mockups were used before constructing the final glove box. TV camera fields of view, placement, and aiming were rapidly changed and evaluated before the testing began. In short, many valuable new insights were gained both before and during this experiment because of the inherent flexibility of the hardware and software.

## DISCUSSION

This study has shown that carefully planned audio-visual and computer workstation hardware can be used effectively to accomplish various kinds of life science procedures remotely and that relatively untrained subjects can learn new life science procedures under the careful guidance of a trained coach. It is important that all participants maintain an overall situational awareness of what is going on at all times. This awareness permits each participant to act in a more closely coordinated manner and to back up the other participants. Lost time due to misunderstandings and procedural errors also are reduced while morale seems to be enhanced. The fact that use of a computer check list slowed the more experienced subjects in task accomplishment indicates a need for a more flexible software working environment that can be tailored to fit the needs of different experience levels.

There are still, however, a number of general concerns which should be raised with regard to the conduct of future teleoperations research. This list is not exhaustive.

1. What is the best mix of manually operated and automated experiments? The answer may depend on whether or not there is a need to carry out many identical steps and/or whether the operation may be hazardous to the human. This study found that manual operations were cost and time effective when the procedures could be modified in real time by the ground controller or the P.I. The P.I. remarked, "This reprogramming was instantaneous." Humans should be permitted to do what they do best and the machines should be programmed to do what they do best.

2. What quantity and quality of data is needed by the remote user? Clearly, each user has different requirements. Further research is needed to define what transmission delays are acceptable in the audio, visual, and digital data channels (Haines, 1989).

3. What specific standardized data, human communications, and control interfaces and protocols are needed within specific scientific and operational disciplines to support the widely varying needs of scientists? The present linked computers transferred alpha-numeric and graphic data at 60 Hz update rate except when certain computationally intensive operations were underway, then screen update slowed markedly. The ground controller and P.I. had to



wait during these delays which effectively prevented them from accomplishing other tasks.

The mouse was the only input device inside the glovebox used by the subject. All subjects found that it could be used effectively to click-off each procedural step. No training was required for its use.

A high quality audio intercom was found to be an important component in this experiment. It had a frequency range of from about 200 to 12,000 Hz. and permitted correct discrimination of voice inflections. This system made it possible to identify the identity of the subject entirely on the basis of their voice (and not video).

4. What is the best mix of distributed (i.e., remote) versus centralized (i.e., payload operations control center) experimental control? Given that both locations have the same degree of data resolution, then either location should be permitted equivalent access to the data base. The final answer will depend on whether there is a need for data security or access control.

5. What is the best way to decide how to allocate limited resources on Space Station to investigators with already approved experiments versus those who have more recently proposed "experiments of opportunity?"

6. What kind of command interlocks and data encryption are needed for critical operations?

## SUMMARY AND CONCLUSIONS

This study has provided a number of lessons learned concerning how three basic kinds of telescience support technology are used to support remote coaching of complex life sciences procedures. They include: (1) The capability to conduct rapid prototyping studies was shown to be a cost-and time-effective way to validate new telescience hardware and procedures, to obtain empirical data, and to gain valuable hardware- and software-related insights. (2) Hardware design will be influenced by the way the test procedures are written. (3) Properly designed audio-visual telescience support hardware will produce higher quality science output on Space Station Freedom. Whether or not computer-based workstations with procedural checklists may contribute significantly to productivity, error control, or workload reduction remains to be seen. Further research is needed in this area.

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## APPENDICES

## Appendix A. Expert Observer Rating Form

Group/Cell No. &amp; Scenario Letter: \_\_\_\_\_

Sheet No \_\_\_\_\_

Rater's initials: \_\_\_\_\_

Subject Initials: \_\_\_\_\_

Test Date: \_\_\_\_\_ 1989

Time: \_\_\_\_\_

*Evidence for any of the following?*

Comments	No	N/A	Yes
a) Savings in crew time: _____			
b) Scheduling flexibility improvement: _____			
c) Productivity enhancement: _____			
d) Science quality enhancement: _____			
e) Enhancement of Safety: _____			

*Was a demonstration given of:*

f) Workstation teleconferencing (to assist flight crew): _____			
g) Video teleconferencing (ditto): _____			
h) Audio teleconferencing (ditto): _____			
i) Effective information transfer: _____			

*Comments and observations regarding interactional telescience modes:*

j) Space to ground in general: _____			
k) Ground to space: _____			
l) Ground to ground: _____			
m) Robot and its control: _____			

*Number and type of errors:* \_\_\_\_\_*Unanticipated Problems:* \_\_\_\_\_

## Appendix B. Informed Consent Form.

Exp. 1-A  
11-15-88

The study in which you are about to take part is designed to evaluate the effectiveness of various telescience operating modes applied to a Space Station mission. For instance, video, audio, and digital communications links will provide you with key information needed to carry out your tasks. You will be considered to be a Mission Specialist on Space Station whose task it is to conduct three separate scientific protocols. You will be alone in the simulated Space Station mockup area. There will be a team of remotely located ground controllers present at all times. In addition, there will be a remotely located "ground expert" available to assist you in certain required operations.

Your involvement will require two, half-day sessions of four hours each. The first half-day will be required for familiarization and protocol training. The second half-day will be used for actual data collection, once it has been determined that asymptotic performance has been achieved. We will try to accommodate your work schedule by your assignment to an AM or a PM session. Rest breaks are planned mid-session. You will be tested two days apart, e.g., either a Monday - Wednesday or Tuesday - Thursday. We will begin the AM session promptly at 0830 hours and the PM session promptly at 1315 hours. All testing will take place in room 115 of building 240A. It is important for you to stay within this area during your work period. Once testing is over a general tour may be given to you upon request.

You will be provided with a NASA flight suit to be worn during data collection. You will not need to bring any special equipment as everything will be provided to you. Feel free to bring a camera for photos if you like.

While every attempt has been made to make the testing environment as safe as possible, there is a small possibility that you may injure yourself. You should exercise caution in moving about within the testing area and in watching out for protruding structures, electrical hazards, or other potentially injurious conditions. Minor first aid will be available in the event you need it. If you Simply explain the situation to your ground controller using the intercom system. You will be monitored continuously via a closed circuit TV camera system. By signing this form below you are recognizing this fact and agreeing to the recording of your voice (audio) and visual image (video) only for data analysis purposes. Under no circumstances will these recordings be made public. In compliance with mandated privacy laws, every attempt will be made to code your data so that another person will not be able to identify you with it at a later date.

I \_\_\_\_\_ (print name) do hereby signify that I understand and agree to all of the above information and testing requirements. I acknowledge that I may leave this test at any time for any reason without prejudice shown towards me.

\_\_\_\_\_  
Signature\_\_\_\_\_  
Date

## Appendix C.

Test Protocols (A) "Seed Germinator Charging",  
(B) "Plant Sample Acquisition and Prerservation," (C) "Remote  
Plant Observation."

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Key: C = flight crew, G = ground controller, PI = Principal investigator (ground expert)

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**(A) *Seed Germinator Charging***

C

1. Close glovebox (GB) vestibule door.
2. Open inner airlock door.
3. Position all items from vestibule to top of inner airlock door.
4. Close inner airlock door.
5. Place several seeds in a germinator paper, fold, and then insert into seed germinator.
6. Place and secure seed germinator within red outline for robot access.
7. Place and secure syringe and holder within yellow outline for robot access.
8. Place and secure distilled water container within blue outline for robot access.
9. Place and secure Hoagland's solution container within red outline for robot access.
10. Click SEND to send a message to the POCC to prepare for monitoring.  
(Advance only after the POCC acknowledges the message)

G

11. Click SEND to initiate robot fluid transfers. Immediately after the robot starts moving advance to the next step.
12. Monitor robot extraction of distilled water.
13. Monitor robot extraction of Hoagland's solution.
14. Monitor injection into germinator.
15. Click SEND to send a message to the crew that the robot activity is complete.  
(Advance only after the crew acknowledges the message.)

C

16. Visually confirm that the robot completed the fluid transfers.
  17. Position all items so that the inner airlock door can be opened.
  18. Open inner airlock door.
  19. Move all items to GB vestibule.
  20. Close inner airlock door.
- End

**(B) *Plant Sample Acquisition and Preservation***

C

1. Close GB vestibule door.
2. Open inner airlock door.
3. Locate all items from vestibule to top of inner airlock door.
4. Close inner airlock door.
5. Open a specimen chamber and remove a single plant.
6. Click SEND to request coaching from ground scientist. (Advance only after the PI acknowledges the message.)

PI

7. Coach crew on tissue removal from apical meristem on root and shoot.
8. Coach crew on tissue sectioning and preparation of two samples for snap freezing.
9. Coach crew on preparation of two samples using glutaraldehyde for chemical preservation.
10. Click SEND to inform crew that the coaching is concluded. (Advance only after the the crew acknowledges the message.)

C

11. Label both frozen and fixed sample containers.
12. Position all items so that the inner airlock door can be opened.
13. Open inner airlock door.
14. Return all items, except for the wet wipes and baggies, to GB vestibule.
15. Close inner airlock door.
16. Wipe down the GB with wet wipes and bag for trash.
17. Open inner airlock door and place trash in GB vestibule.
18. Vacuum GB work volume and vestibule.
19. Close inner airlock door.

End

### (C) *Remote Plant Observation*

C

1. Close GB vestibule door.
2. Open inner airlock door.
3. Move plant chamber and baggies from vestibule to top of inner airlock door.
4. Close inner airlock door.
5. Remove plant specimen from plant chamber and replace lid.
6. Place and secure leaf within green lined examination square for down looking camera observation.
7. Click SEND to send message to ground expert to examine leaf color and morphology. (Advance only after the PI acknowledges the message.)

PI

8. Tell the crew approximately how long the diagnosis will take.
9. Diagnose the plant for specimen health.
10. Click SEND to send a message to the crew to reposition specimen. (Advance only after the crew acknowledges the message.)

C

11. Place and hold leaf on yellow intersection on GB wall for IR scan.
12. Click SEND to send message to the ground expert to start IR scan. (Advance only after the PI acknowledges the message.)

PI

13. Perform the IR scan.
14. Click SEND to send a message to the crew to reposition specimen. (Advance only after the crew acknowledges the message.)
15. Coach crew how to hold specimen for optimal view of venation.
16. Consult with a NASA plant pathologist at the POCC to evaluate calcium levels in nutrient solution and daylength period..

17. Instruct crew to adjust daylength setting on the habitat appropriately.
- C
18. Adjust daylength setting if necessary.
19. Insert plant chamber in plant habitat.
20. Bag used cleaning materials for trash and place in GB vestibule.
21. Open inner airlock door.
22. Move all items to GB vestibule.
23. Close inner airlock door.
- End.

1. 1. 1.

2. 2. 2.

3. 3. 3.







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